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Title: Development and operation of Pulse Magnet at LANL's PFF

Author(s): Nguyen, Doan Ngoc

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Development and operation of Pulse Magnet at LANL's PFF

Doan N. Nguyen



OUTLINE

1. Overview of Pulsed Field Facility at LANL
2. Performance and design improvement of 65 T workhorse magnets
3. Performance, failure and rewinding progress of 60 LP
4. Performance and challenge of 100T
5. Introduction of future 80 Duplex magnet
6. Discussion on proposed plan to go beyond 100T
7. Some examples of cutting edge high-field science

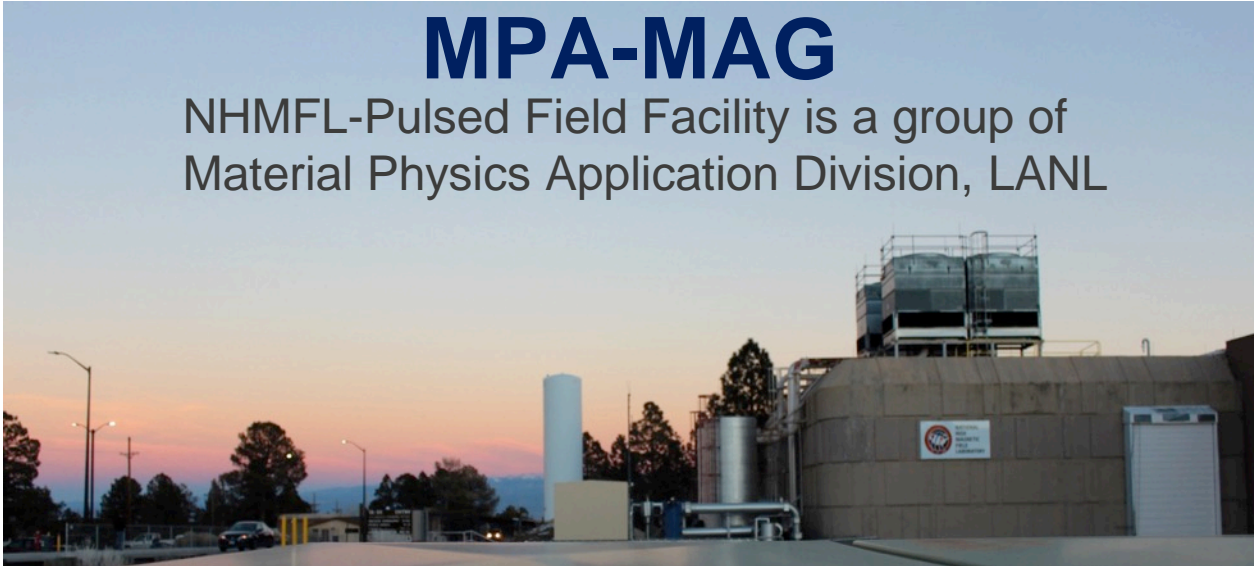
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OVERVIEW OF NHMFL's PFF at LANL

MPA-MAG

NHMFL-Pulsed Field Facility is a group of Material Physics Application Division, LANL



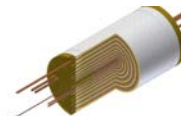
Our mission is to provide:

Extreme magnetic fields at the Pulsed-Field Facility in support of the National High Magnetic Field Laboratory's User Program

<http://nhmfl.lanl.gov>



NHMFL User Program



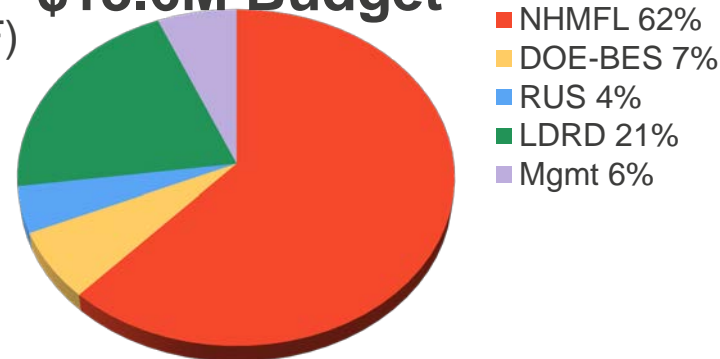
Magnet Engineering



High-Field Science

MPA-MAG Primary Projects

\$13.6M Budget



- **Strategic Partnership Projects**

- NHMFL-Pulsed Field Facility User Program (FSU/NSF)

- (~\$8.4M/yr x 5)

- **DOE – Basic Energy Sciences**

- Science of 100 Tesla

- (Harrison **\$0.9M/yr x 3**)



Neil Harrison

- **Weapons & Global Security Programs**

- Science Campaign 1 & 2: Aging & EOS via RUS

Resonant Ultrasound Spectroscopy

- (Maierov Co-I **\$0.396M**)



Boris Maierov



Scott Crooker

- **LDRD – Directed Research**

- Defect Induced Emergent Magnetism

- (Crooker ER 2015 **\$0.34M x 3**)

- Fluctuating Domains in Antiferromagnets for Sensing and Switching Applications

- (Zapf ER 2017 **\$0.35M x 3**)

- Electronic Structure of putative topological Kondo insulators

- (Chan ER 2018 **\$0.32M x 3**)

- Scalable dielectric technology for VLF antennas

- (Singleton ER 2018 **\$0.296 x2**)

- Uncovering the role of 5f-electronmagnetism in the electronic structure and equation of state of plutonium (U)

- (Harrison DR 2018 **\$1.52M x 3**)



Mun Chan



John Singleton



Vivien Zapf

What is Unique @ the NHMFL

- **1.43 Billion Watt Generator**

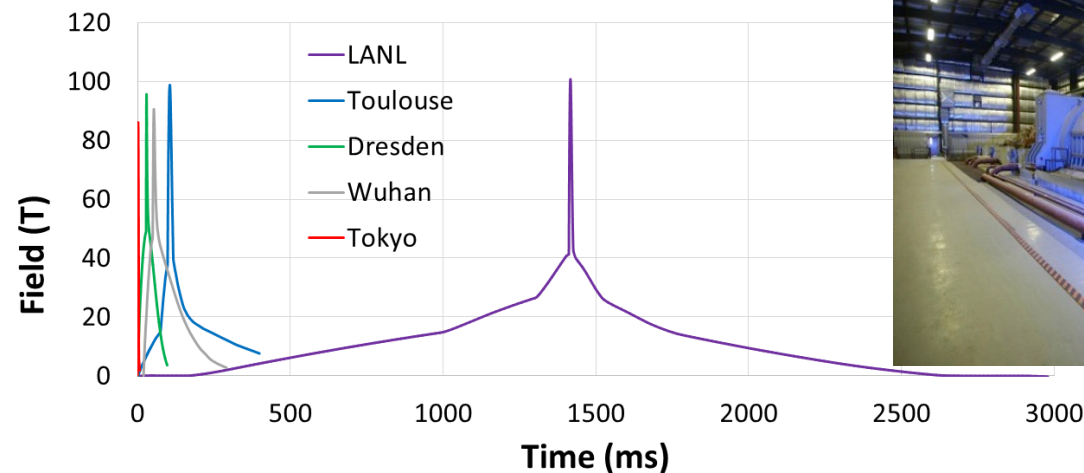
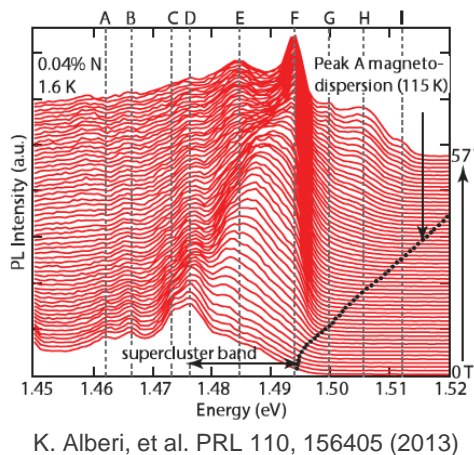
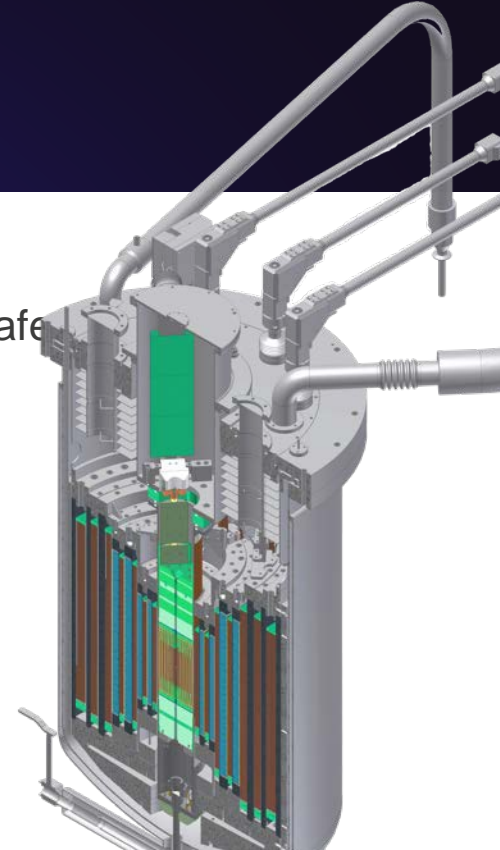
- Capable of delivering 600 Mega-Joules of electrical energy in a safe and reliable manner many times each day

- **100 tesla non-destructive magnetic fields**

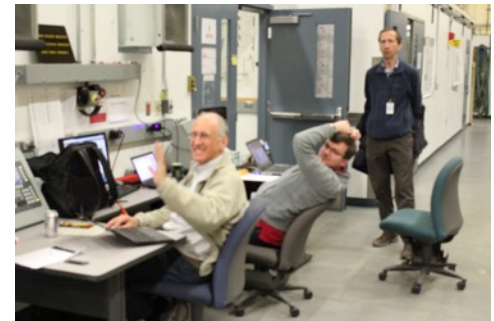
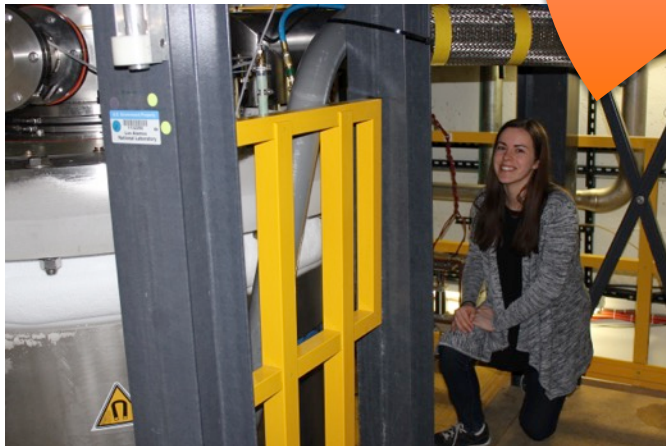
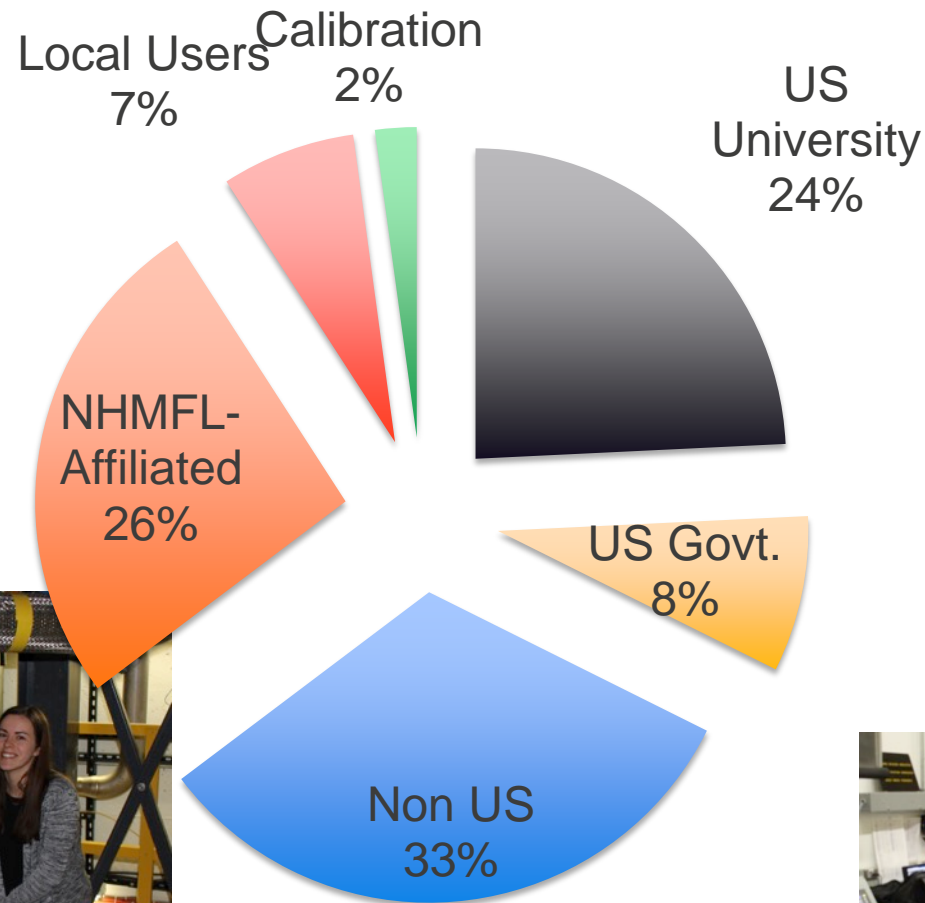
- More than 10000 times longer duration pulse = unprecedented scientific resolution

- **60 tesla controlled waveform magnet**

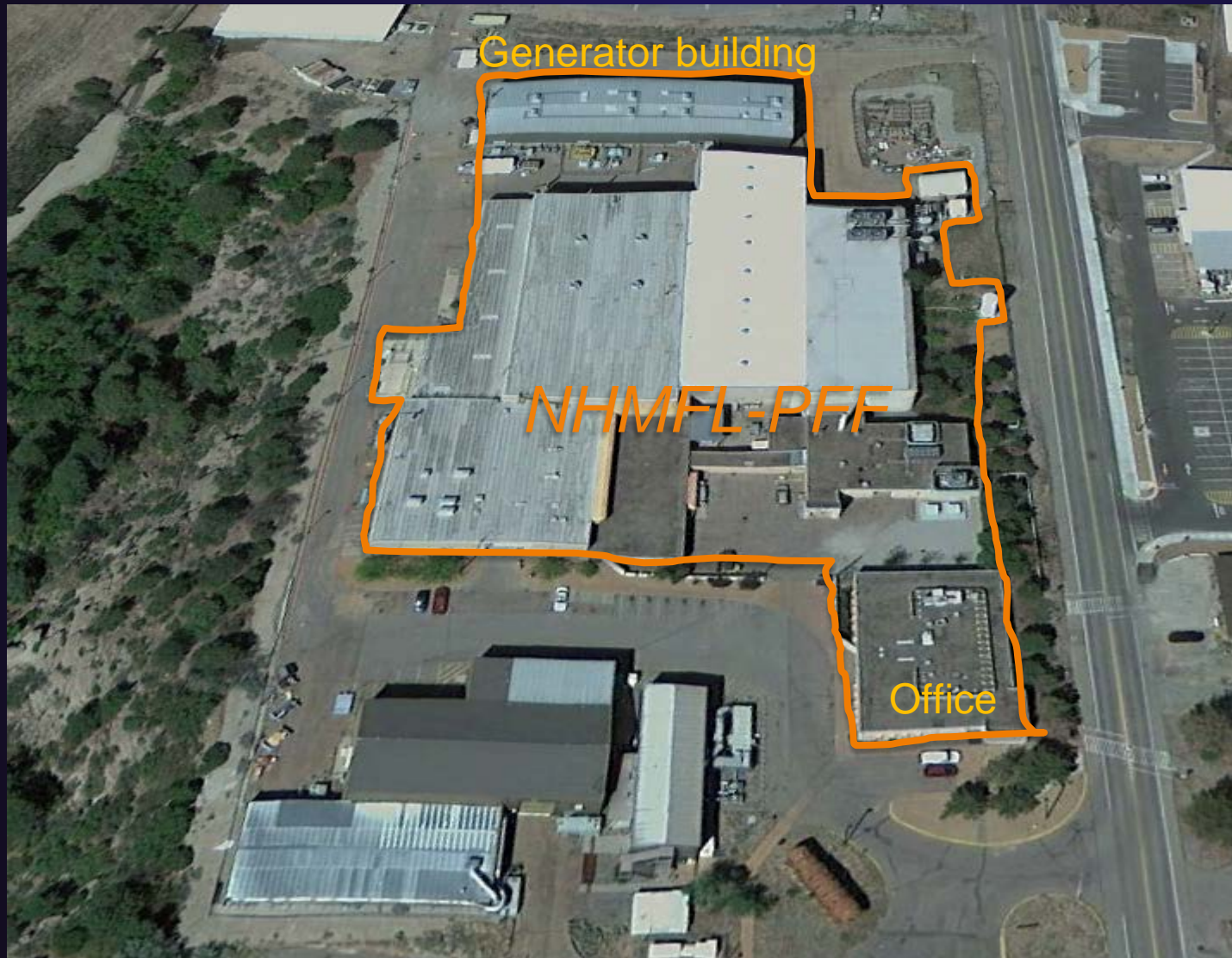
- Heat capacity (relaxation method)
- High resolution photo-luminescence
 - True optical spectroscopy (1000s of spectra)



Where do NHMFL-PFF Users come from?



The Pulsed Field Facility



60,000 ft²
16 Magnet
stations

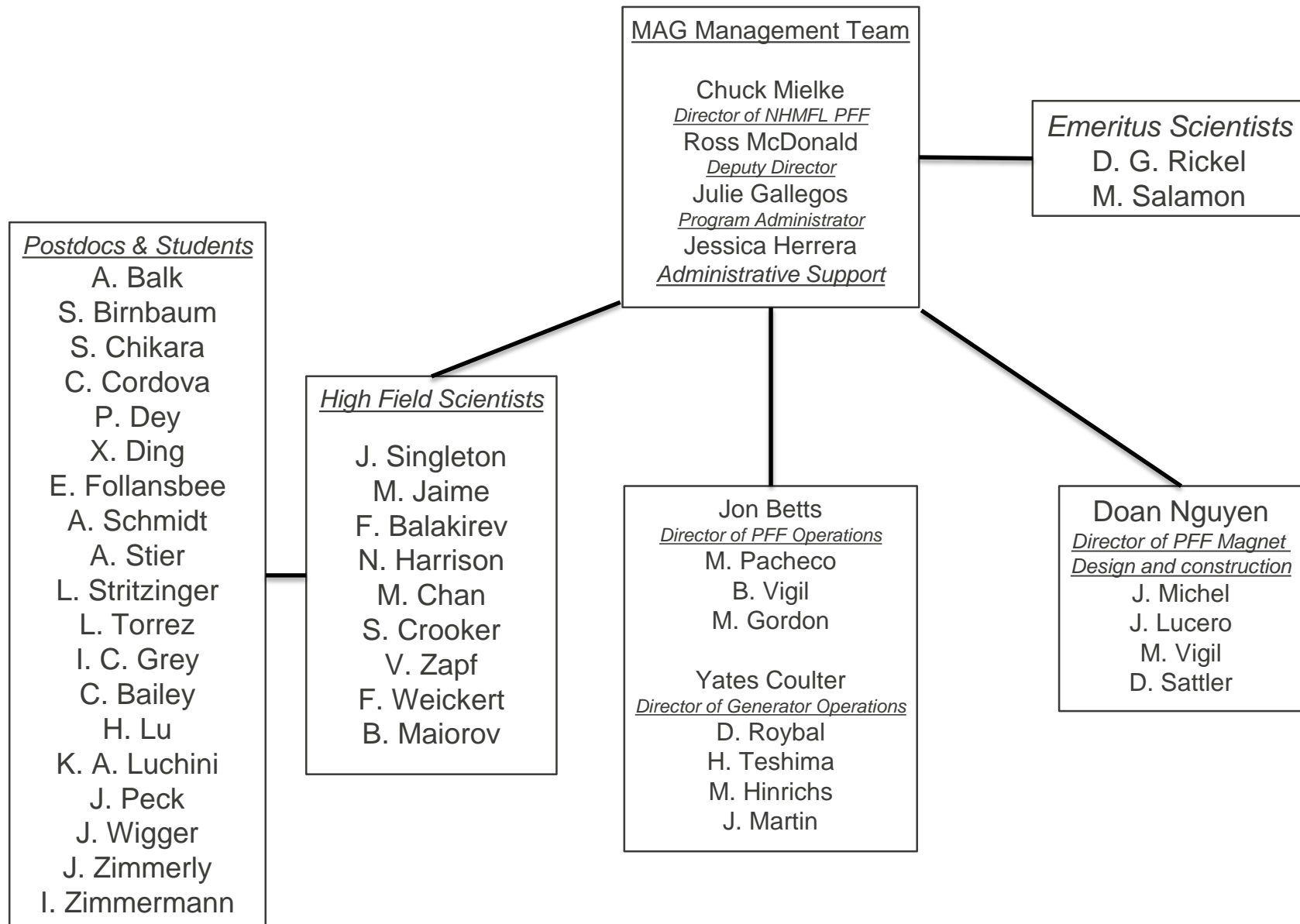
10 Pulsed
6 SC

13 Scientists/Eng
9 Technicians
6 PDs
13 students
3 Admin
2 Eng Contract

46 Total People

200 users/yr

MPA-MAG Organizational Chart July 2017



Strategically investment in Helium recovery

- Helium liquefaction *Investment* avert major issue with helium access for users
- Recovery rate ~90%

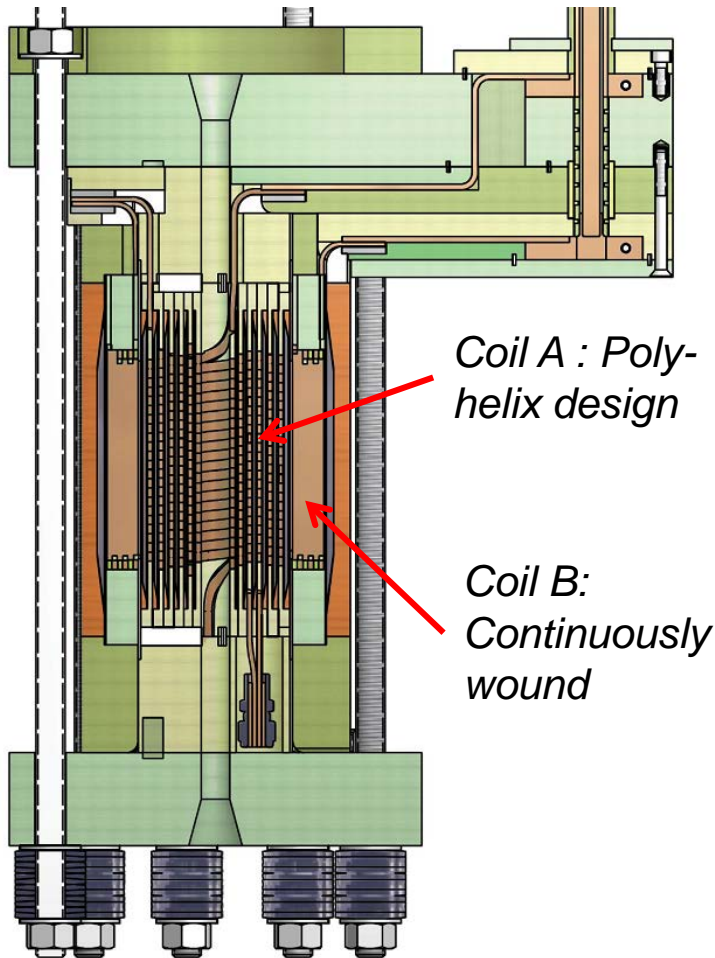
- FSU major Equipment
- LANL G&A funds paid for NHMFL Labor, safety engineering and utility installation costs



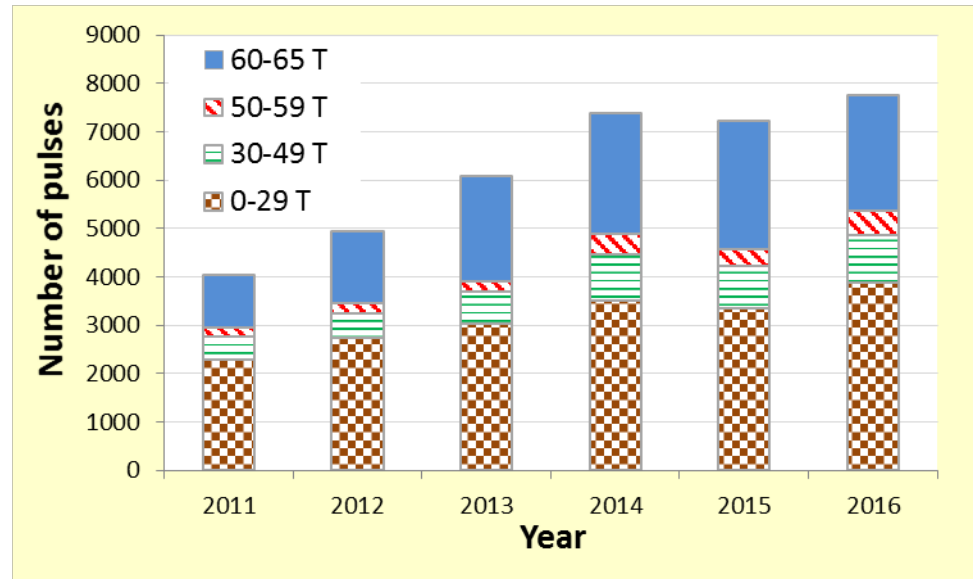
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65 T workhorse magnet operation



Overview of 65 T magnet cross-section



- 4 cells of 65 T magnets
- More than 7000 shots in last three years
- ~2500 shots above 60 T
- 4 - 6 magnets failed each year

65 T Workhorse Magnet – Redesigned reinforcement of coil A

Installing wraps of MP35N thin strip is challenging and time consuming:

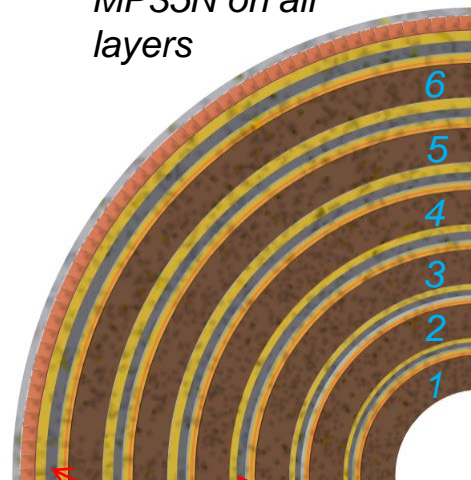
- difficult to pack MP35N strip tightly due to its ripple and non-uniform thickness



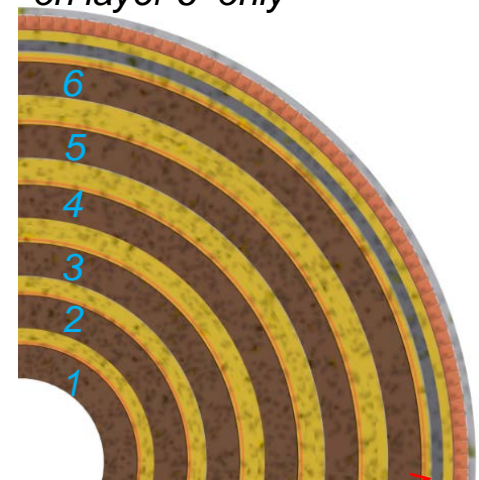
Replacing MP35N by Zylon fiber and S2-glass tape composite helps:

- Reduce the manufacturing time significantly, improve the quality control
- Mechanically stronger
- Reduce the material cost (MP35N strip is expensive)

Old design with MP35N on all layers



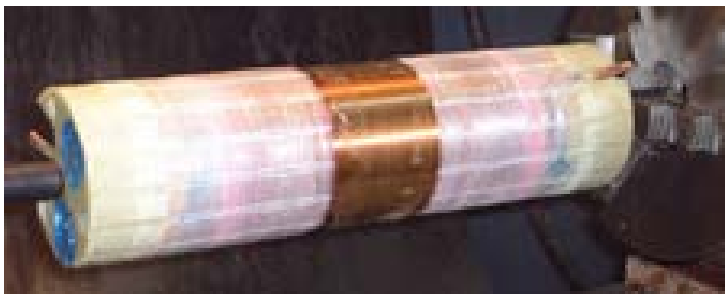
New design with MP35N on layer 6 only



MP35N

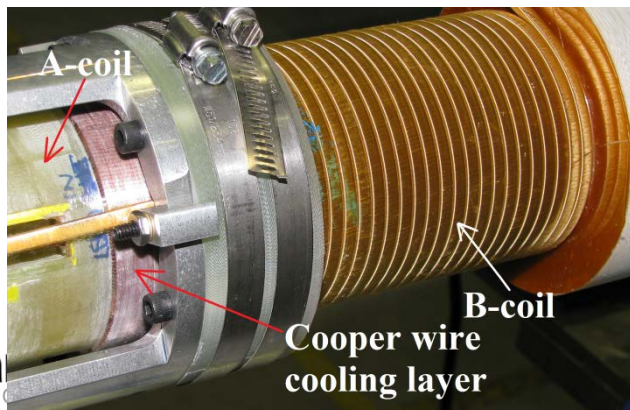
65 T Workhorse Magnet – New cooling technique

Without cooling channels, magnets take 2.5 hours for cooling



Cooling channels on coil A for LN to flow between coils A and B : Cooling time down to 25 – 30 minutes

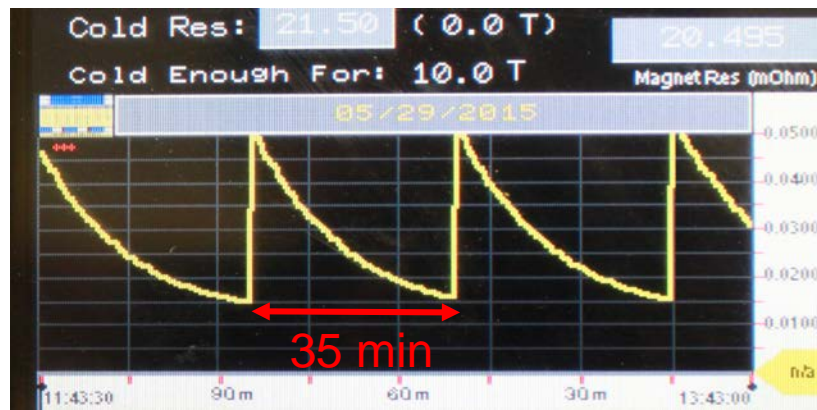
New cooling technique: layer of insulated, 16 gauged copper wires laid along coil A. No eddy current issue, no mechanical impact, good thermal efficiency



Damages



Issue: Conductor of coil B collapsed into cooling channels due to post-pulse compression, causing instability and wire insulation damage



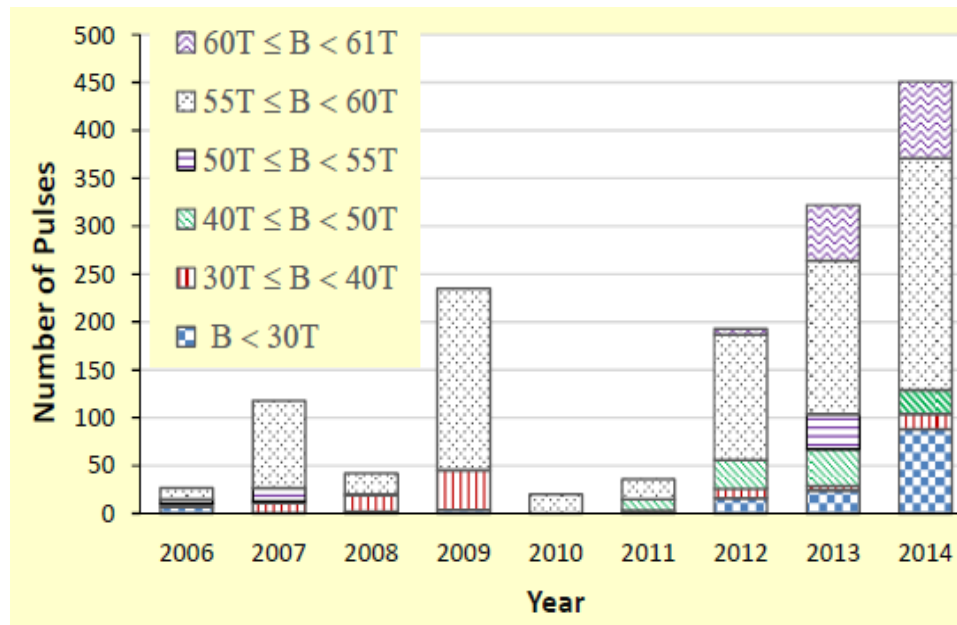
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60 T Controlled Waveform Magnet



- Consists of 9 nested coils, powered by 1.4 GW generator
- 60-T peak field in 32 mm bore
- 2500-ms pulse length with 100-ms flattop
- Controllable waveforms to meet some special requirements from user



- First assembly failed in 2000
- Rebuilt magnet started operating in 2006
- Soft failure at mid-plane of coil 7 in December 2014.
- Totally, delivered 1453 shots, 144 shots with $60 \leq B \leq 61\text{T}$ and 888 shots with $55 \leq B \leq 60\text{T}$

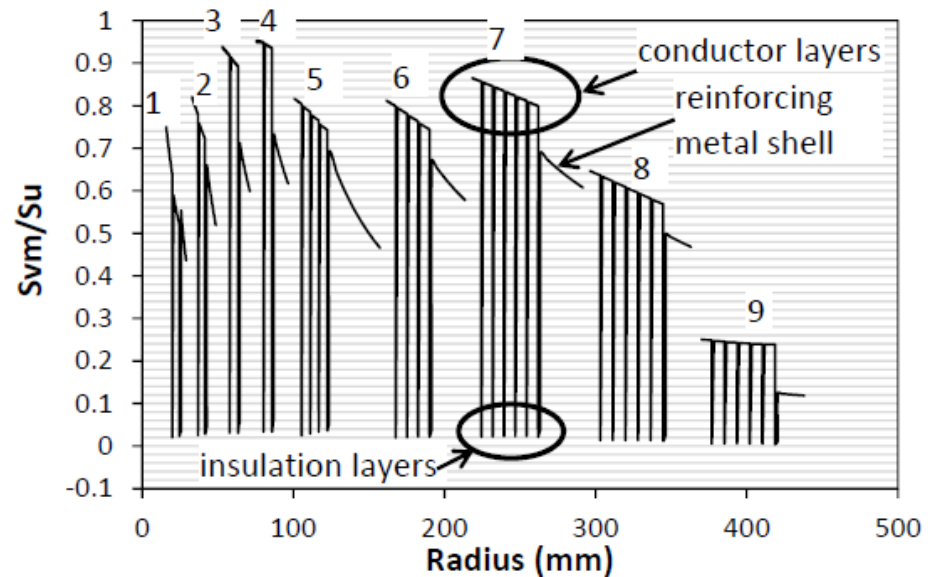
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Slide 16

Mechanical Performance of 60 T Controlled Waveform Magnet

- von Mises stresses in coils 3, 4 and 7 are the highest
- $S_{vm}/S_u \sim 0.95$ for conductors in coils 3 and 4
- Stress in conductor of coil 7 also reaches ~ 0.87 of the ultimate stress
- These results explain for considerable dilation of mid-plane of coil 3,4 and 7, observed from autopsy after magnet's failure. Other coils are ok!

Mid-plane von Mises stress normalized to the ultimate stress (S_{vm}/S_u) for all 9 coils for a typical 60 T shot

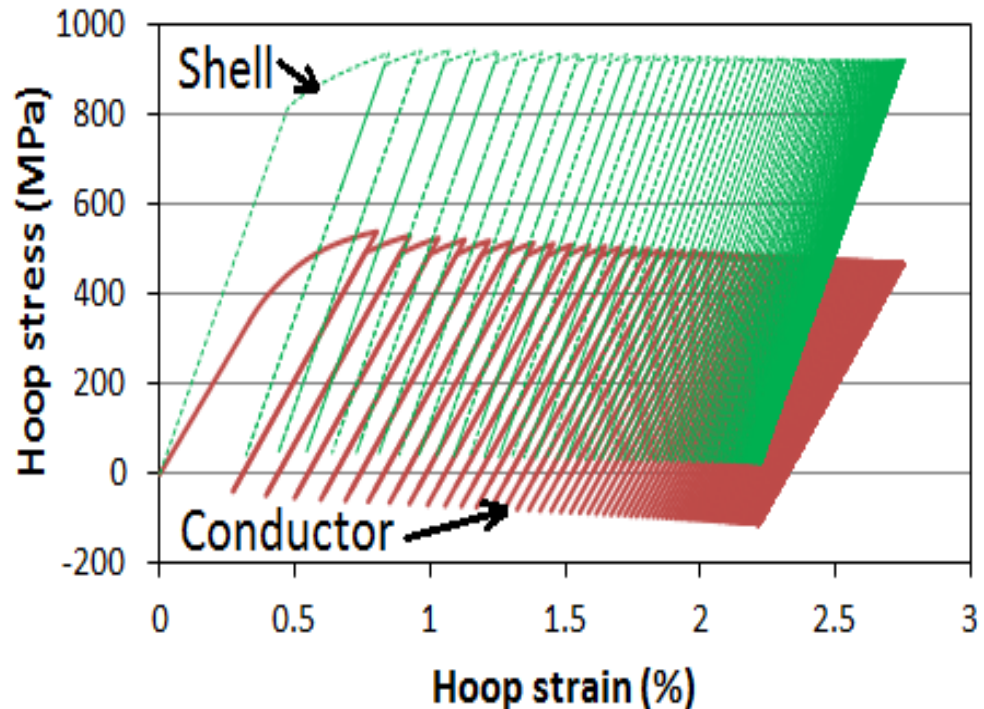


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Slide 17

Understanding the dilation in 60 T CW magnet by preliminary cyclic simulation

- Magnet delivered 195 shots with $59 \leq B \leq 61$ T
- Using data from fatigue tests of conductors/reinforcing material, preliminary cyclic simulations for 195 shots of 60 T have been done
- In no-load condition after each pulses, conductor is compressed due to plastic elongation while the shells is stressed as expected.



Stress-strain relation in hoop direction for the conductor and reinforcement shell of coil 4 (the weakest coil) after 195 shots at 60 T

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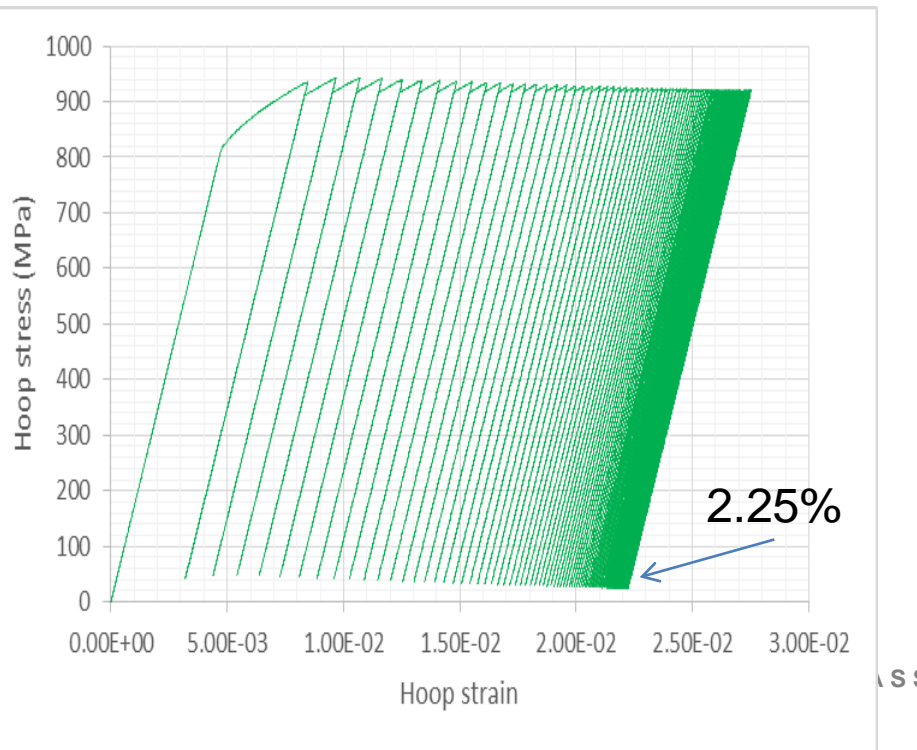
Slide 18

Cyclic calculation for 60T CW magnet

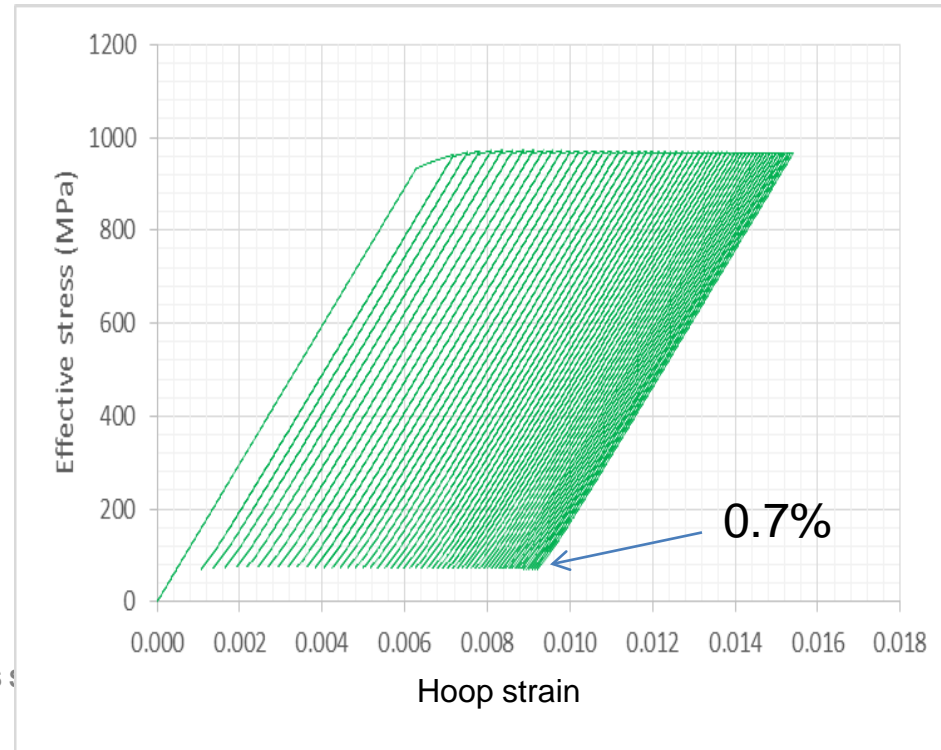
Performed for 195 cycles of full field:

- Residue hoop strain of Ni40 metal shell of coil 4 is 2.25 %
- Residue hoop strain of Ni40 metal shell of coil 7 is 0.7 %
- The computational results are close to the reality (within 20%)

Hoop strain in metal reinforcement of coil 4



Hoop strain in metal reinforcement of coil 7



Autopsy of the failure of coil 7 – 60T LP magnet



Happen in several turns near the mid-plane



Wire completely fractured at only one location



Wire shorten and deformed due to heating and asymmetric compression



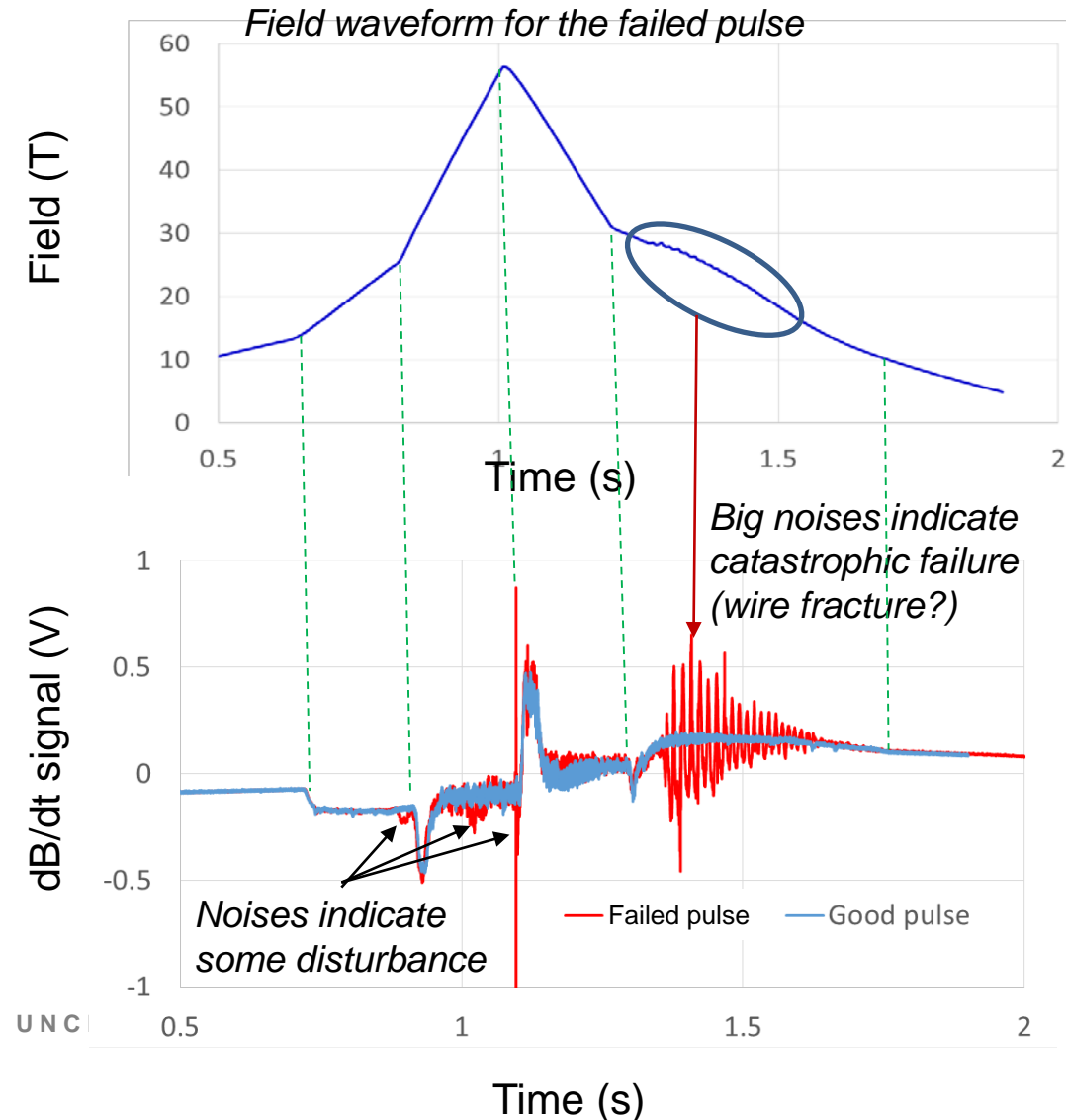
Arcing turn-to-turn all around the coil



Severe arcing between layer 1 to layer 2

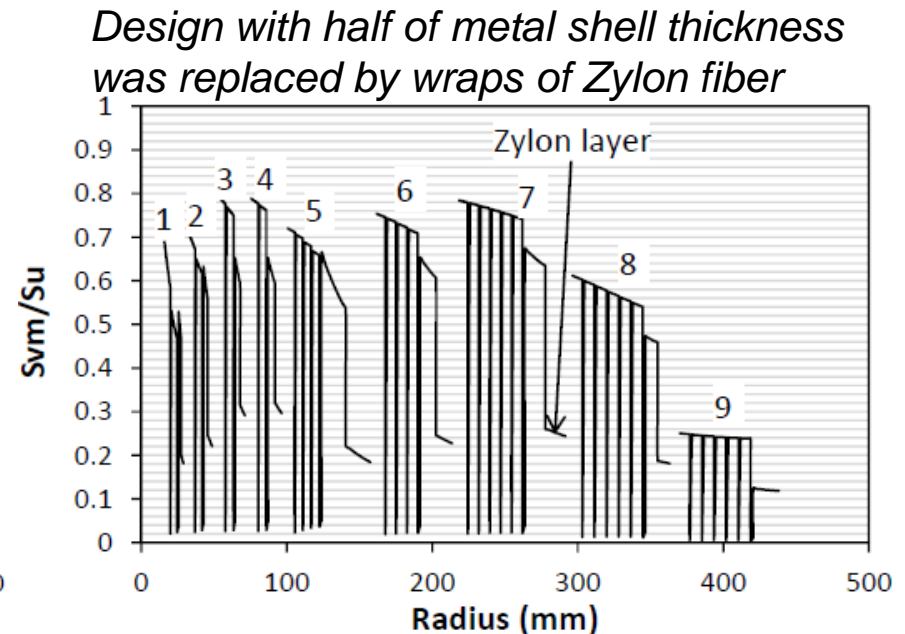
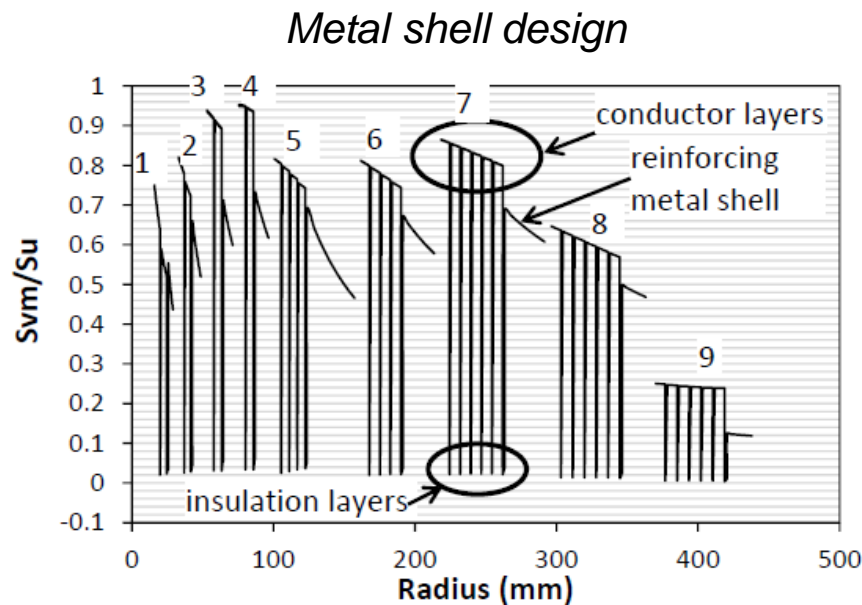
Autopsy of the failure of coil 7 – 60T LP magnet

- Driven by three power supplies
- dB/dt signal for the failed pulse shows some low noises in the first half of the pulse (arcing starts and propagates?)
- Larger noise happens in the second half of the pulse indicate a catastrophic failure (wire fracture?)
- The insulation breakdown initiated the failure
- That prediction is also reasonable because both calculation reality show considerably higher stresses in coils 3 & 4 which are still survive
- Wire insulation need improvement and better quality control



Proposed plan to improve mechanical performance for 60 T CW magnet

- Magnet is a very important, versatile tool for our users => will be rebuilt asap
- Partially replacing the metal reinforcing shell with wraps of Zylon fibers, especially for coils 3, 4 and 7, can improve the mechanical performance



- More analyses will be carried out for better optimization
- The proposed approach using Zylon fiber does not require significant structural modifications and would not affect the manufacturing time

Production of 60T LP magnets at NHMFL-FSU campus

- Need to rebuild coils 3, 4 and 7 for 60 T LP magnet
- Developed winding capability at NHMFL-FSU to wind big pulsed magnet coils: better quality control, more R&D work
- Production of a model coil was finished, production of 3 and 4 will be started soon

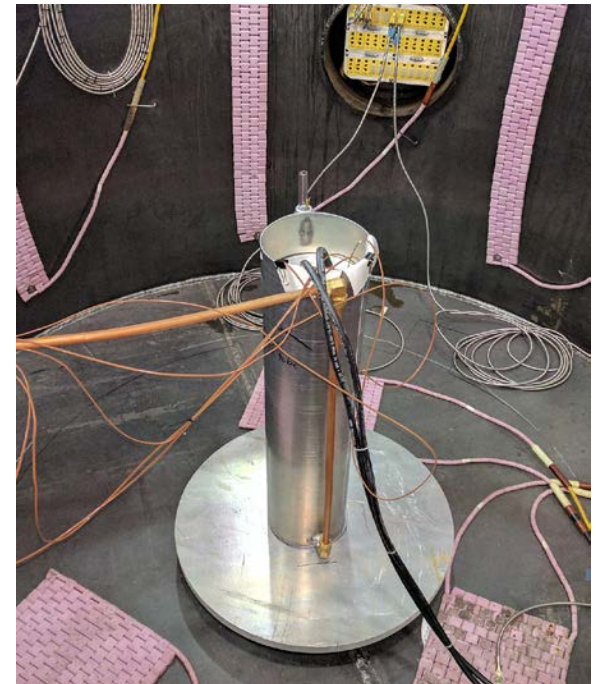


Winding the coil



Installing the lead

In chamber, ready for Vacuum Pressure Impregnation (V.P.I)

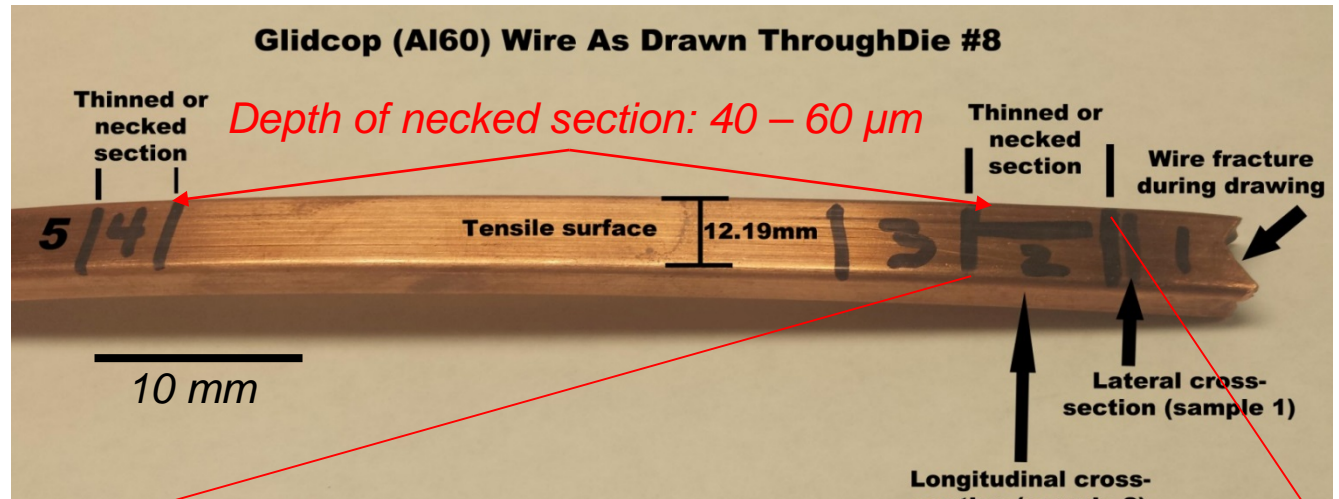


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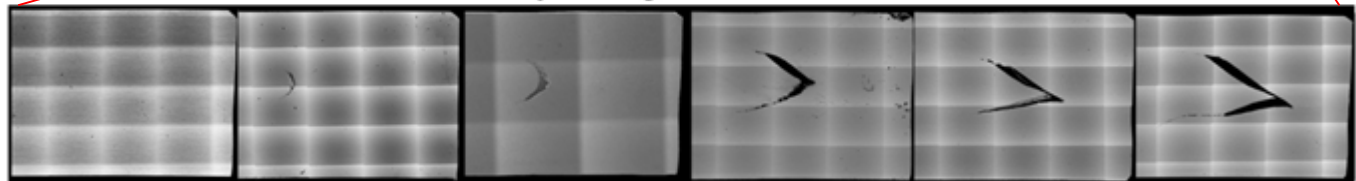
Chevron breakage during drawing of wire for coil 7

- Glidcop AL60 wire for coil 7 needs 10 drawing passes (dies) to meet mechanical strength
- Wire was fractured at pass #8
- Wire has thinned (necked) sections which are difficult to detect with bare eyes

Courtesy of
Robert Goddard



Sample 2 - Longitudinal Cross-sections



Distance from edge 2.22 mm 4.68 mm 5.68 mm 6.24 mm 7.24 mm 8.36 mm

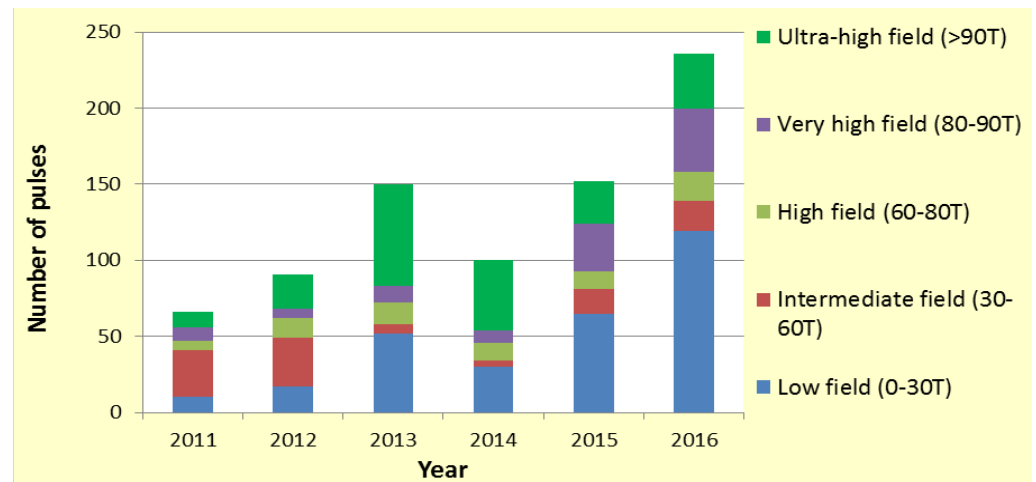
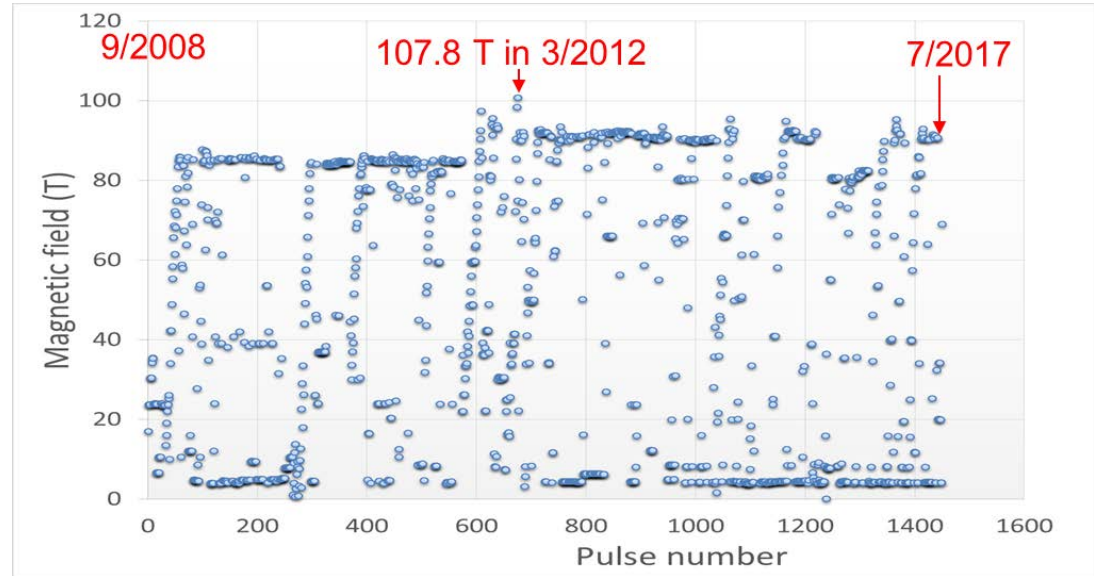
- Detect Chevron cracks inside wire at thinned section
- Investigation to improve drawing process (change die schedule, die angle, drawing speed, lubricants) is underway to produce good wire for coil 7
- May need to inspect the wire for internal crack before winding (Xray, ultrasonics)

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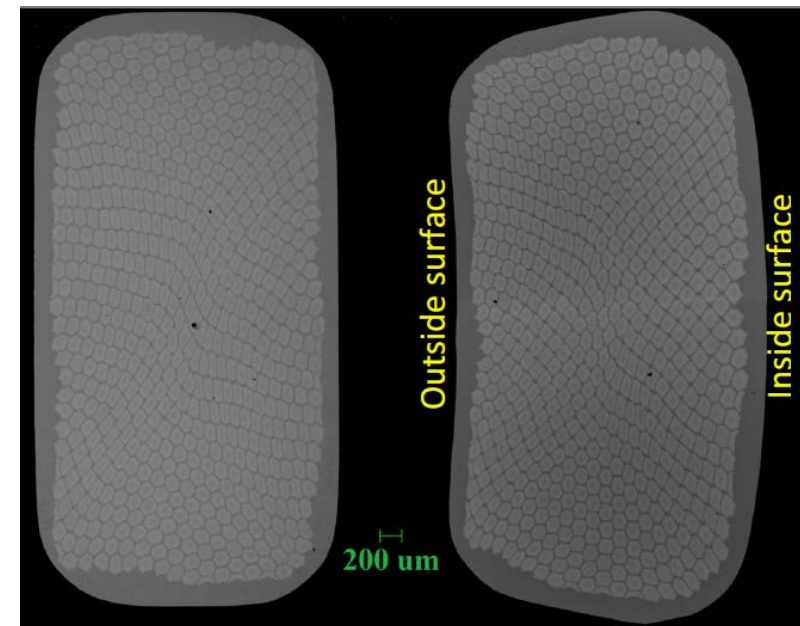
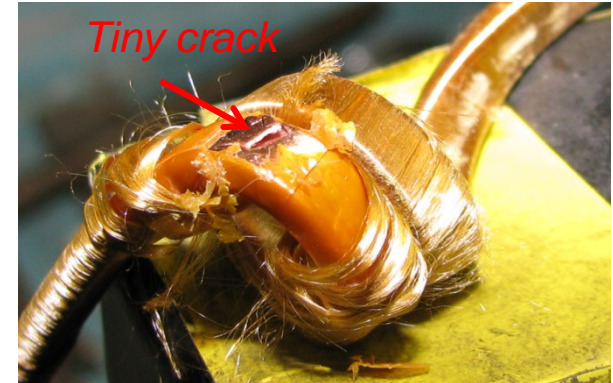
100 T multi-shot magnet performance

- Total ~ 1500 shots
- 230 shots above 90 T
- 560 shots above 80 T
- 3.5 hours cooling time between full field shots
- Faster cooling design (2 hours) is desired and being developed



100 T Multi-shot Magnet - Conductor Issue

- Use Cu-Nb nano-composite wire (UTS ~1.2 GPa at 297K)
- Mechanical properties not very consistent over long length or between purchases
- Wire sometimes get fractured when wound on 10-mm OD mandrel for 100-T magnet
- Effect of small radius bending on conductor deformation/strength must be investigated
- The wire experienced a considerable deformation as wound into 10 mm bore helix
- Areas of Nb filaments increase by ~ 16 % near the inside surface and decrease by 19 % near outside surface.
- Wire compressed 6% inside and stressed 19% outside
- For more details see presentation 4OrBB_03



Original

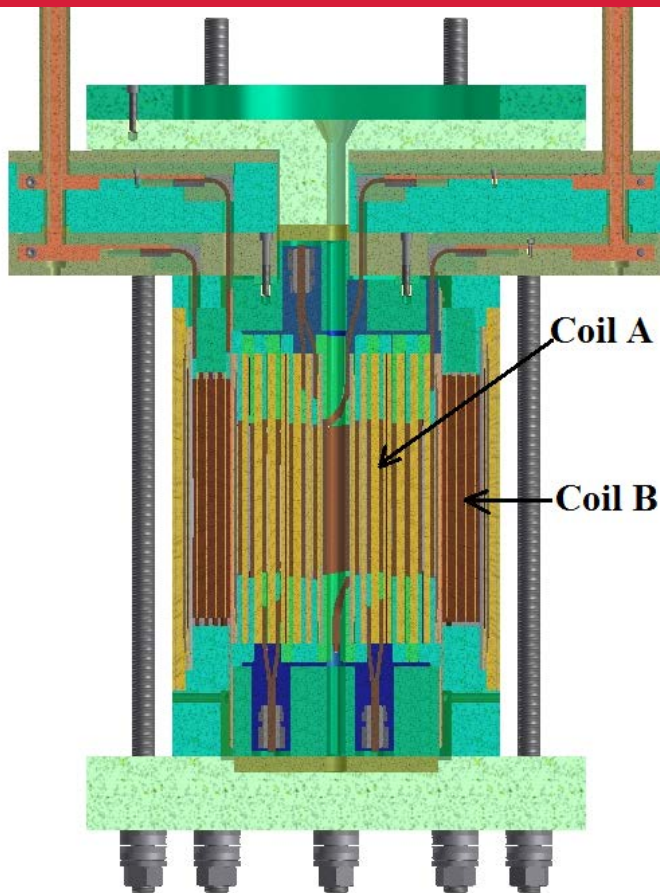
100 T innermost layer

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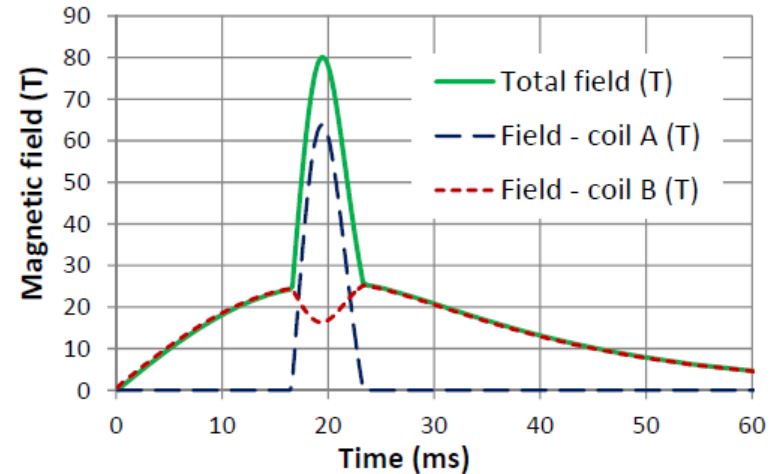
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Prototype 80 T Duplex Magnet



Overview of 80-T duplex magnet
(15 mm bore, coils A and B
independently driven by 2 cap-banks)



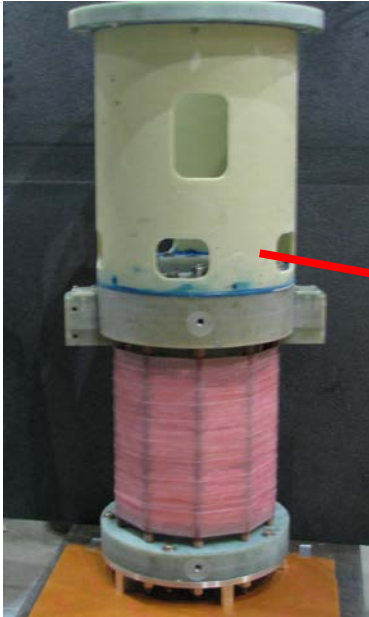
Field profile for a 80 T

- For the 80 T shot, the maximum $S_{vm}/S_u = 0.8$ for conductor and $= 0.58$ for reinforcement materials
- Should have lifetime for 1000 shots of 75 T for regular operation
- Scheduled to be tested in Jan 2018

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Slide 29

Construction of 80 T duplex magnet and user duplex cell were completed



1st duplex magnet



User duplex cell with housing
for magnet under the platform

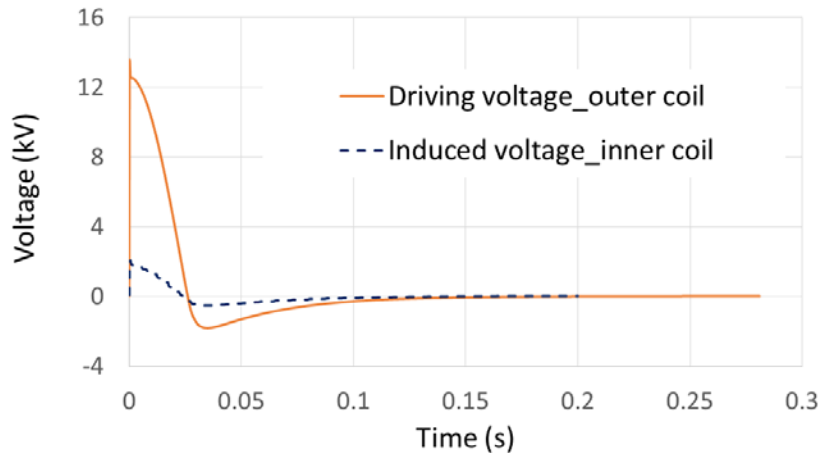
- 4 MJ capbank will be shared between duplex magnet and four 65 T magnets
- Capbank was modified and reconfigured so that the test and operation of duplex do not impact much on operation of our workhorse 65 T magnet
- Construction of duplex cell with user platform was completed

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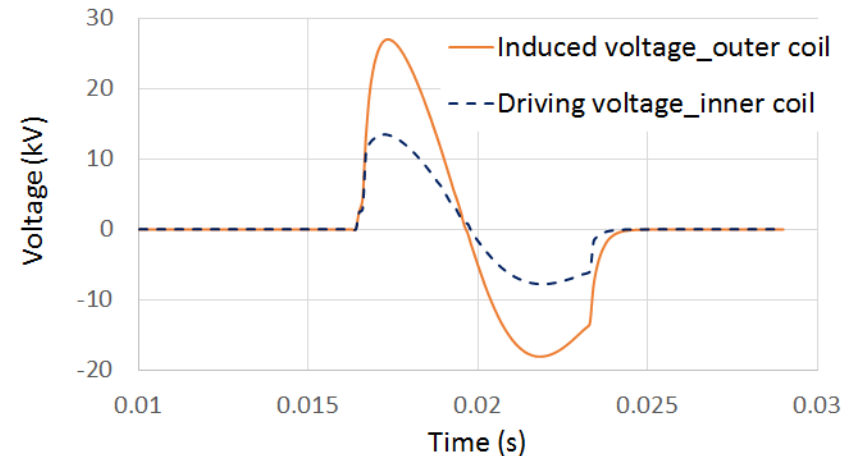
Slide 30

MOV protection bank was designed and now under construction

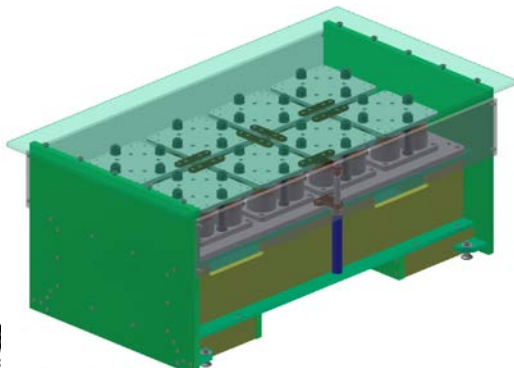
What happen if “misfired” situation occurs with a 80 T shot?



- Outer coil is energized with 14 kV generated induced voltage of ~2 kV on the inner coil if it is in open circuit



- Inner coil is energized with 13.5 kV generated induced voltage of ~27.2 kV on the outer coil if this coil is open
- Thin MP35N layers with their low electrical conductivity do not help much in decoupling between the coils



Need a metal oxide varistor bank connected in parallel to the outer coil to protect its capbank and control electronics

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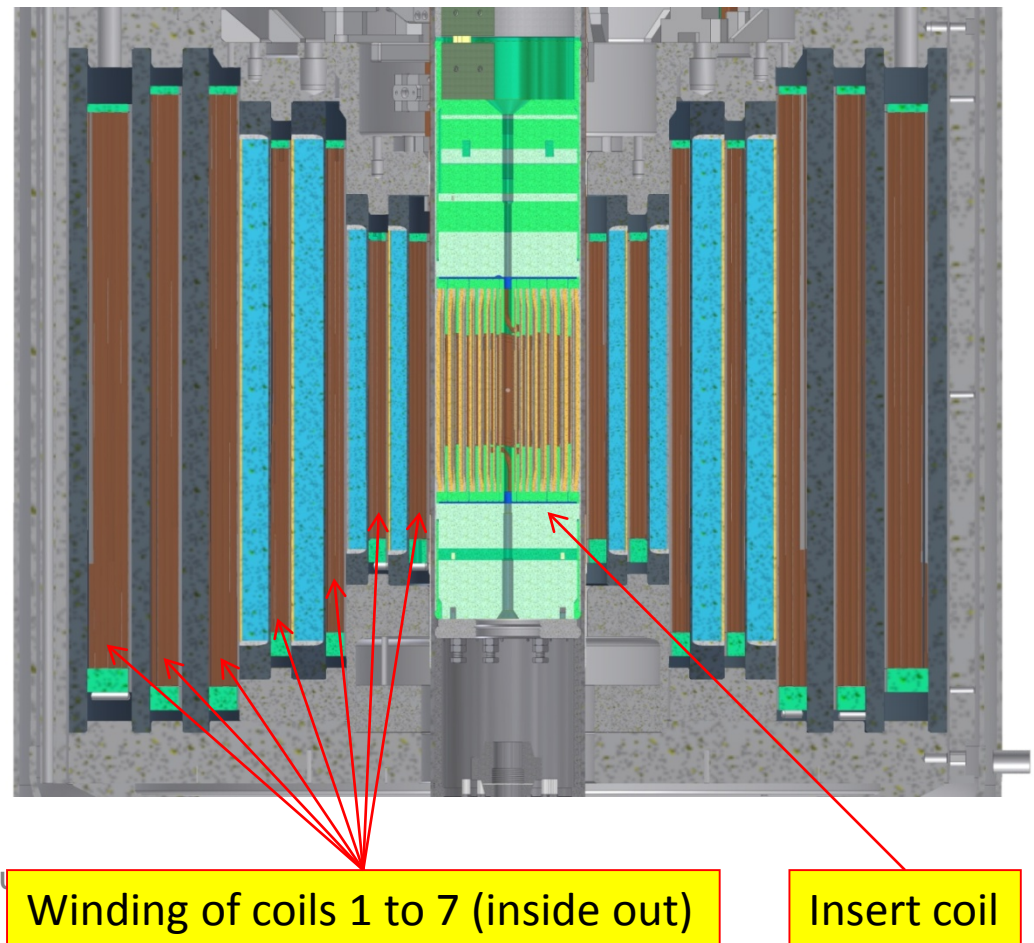
Propose to upgrade the present 100 T magnet in the new funding cycle (2018 -2023)

Proposal was submitted fall 2016, should receive final decision of NSF this fall:

- Upgrade the present 100 T magnet to the range of 115 -120 T

Field contribution (100.8T):

- Outsert's coil groups driven by 3 power supplies powered by a 1.4GW generator
- Outsert: 40.6T (2500 ms)
- Insert : 60.1T (15 ms, c-bank)
- Maximum magnetic energy at 100 T: 153 MJ
- Ohmic loss: 90 MJ



Approach for 115 T using upgraded outsert magnet

Remove C1 and C2 of the outsert magnet to use that space for insert windings with much higher current density



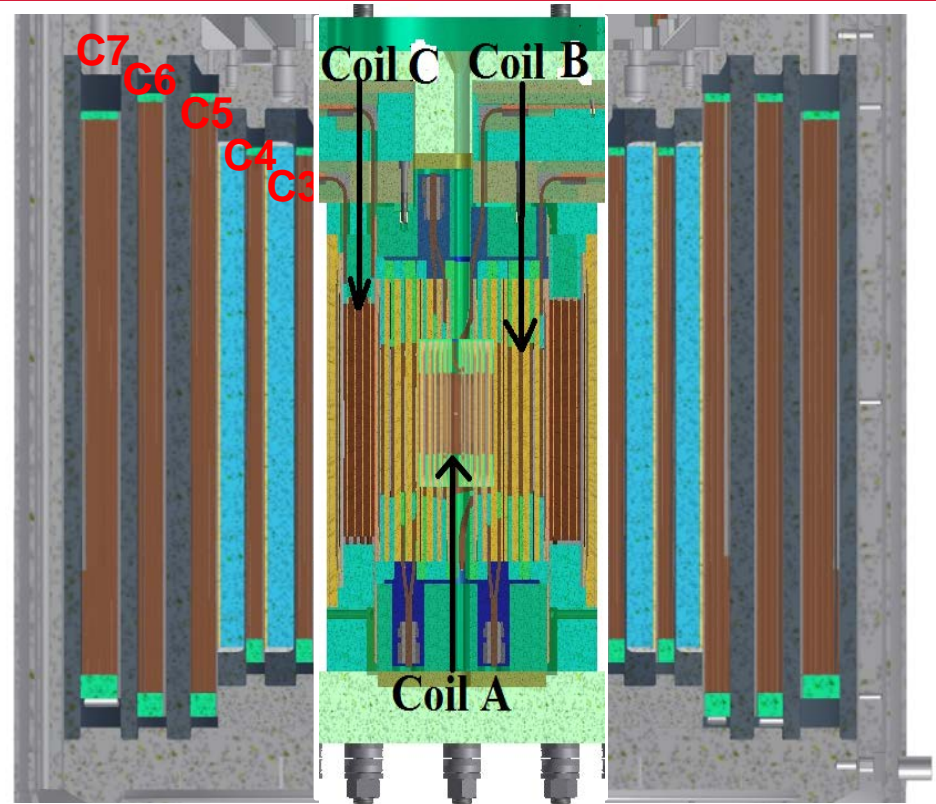
Upgrade/redesign C3 and C4 to provide background field of 30 T in 45 cm bore:

- Use better conductor (CuNb wire)
- Replace SS301 shells by a combination of Ni-40 and Zylon



Use triplex insert powered with new cap-banks:

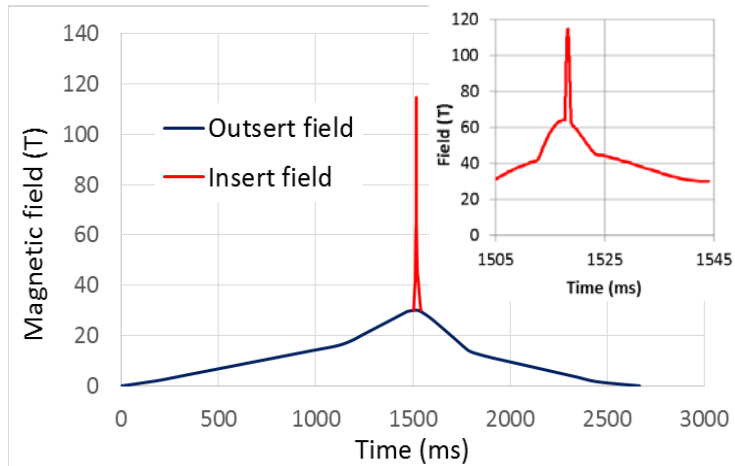
- Require new 30 kV, 11 MJ Capbank



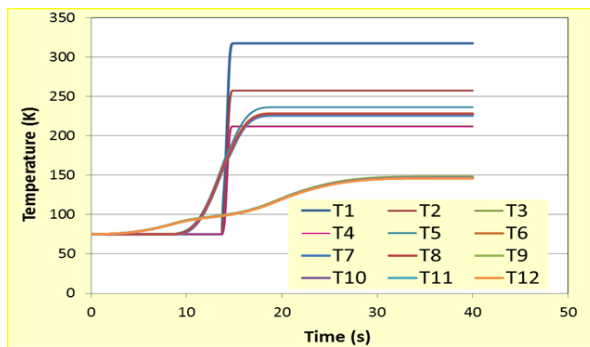
We current have spare coils for C5, C6, C7, it is possible that we can build a new 115 T if funding is available:

- *New pit with supporting structure*
- *New C3 and C4*
- *New capbank*

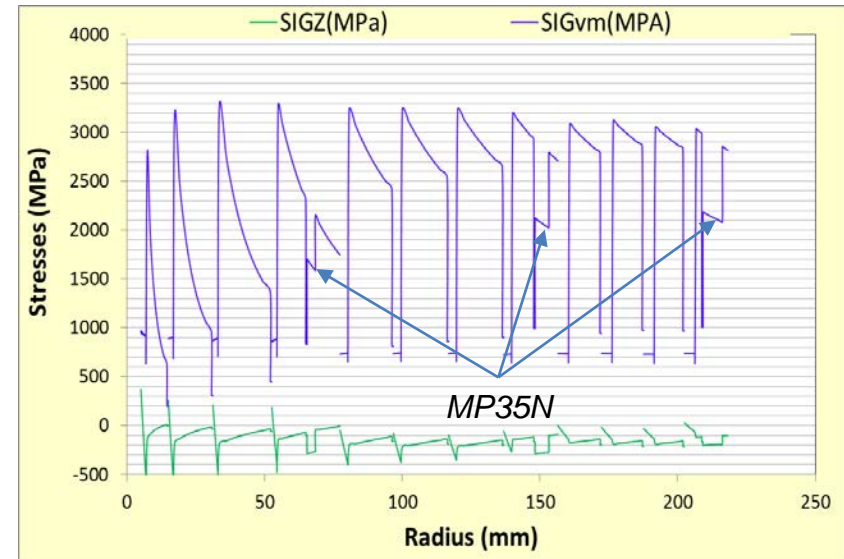
Field profile for 115 T magnet and mechanical/thermal performance of the insert coil



85 T triplex insert in 30 T background field



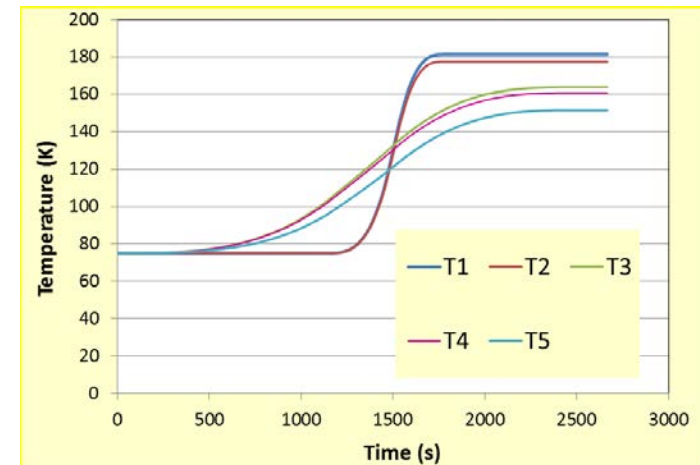
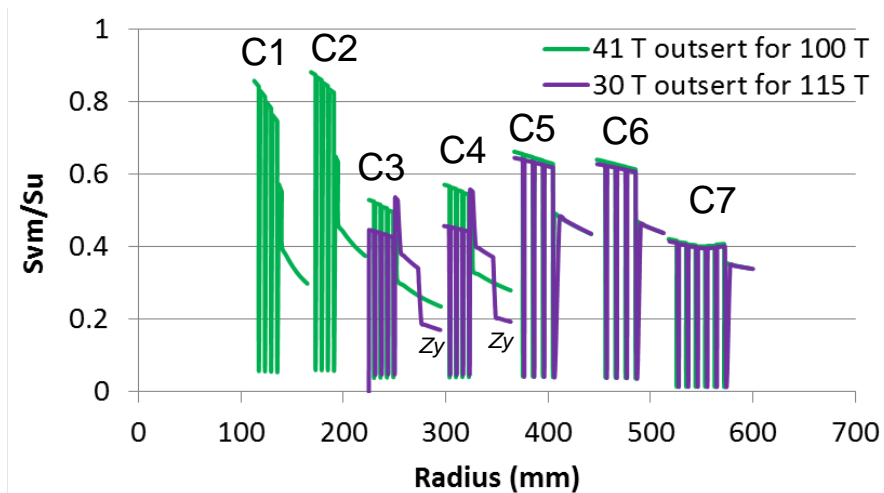
Temperatures in all 12 winding layers during a full field pulse are below 350 K



Stress level of the insert for a full-field pulse:

- Peak Von Mises stress in Zylon 3300 MPa
- Peak compression axial stress is 500 MPa
- Higher risk in lower energy coil, expect the inner most coil fails first
- MP35N layer outside each sub-coil to prevent failure to transfer from low energy coil to high energy coil

Mechanical and thermal performance of 115-T outsert compared to present 100 T



Normalized stress S_v/S_u in the present 100T outsert and proposed wide-bore outsert for 115T

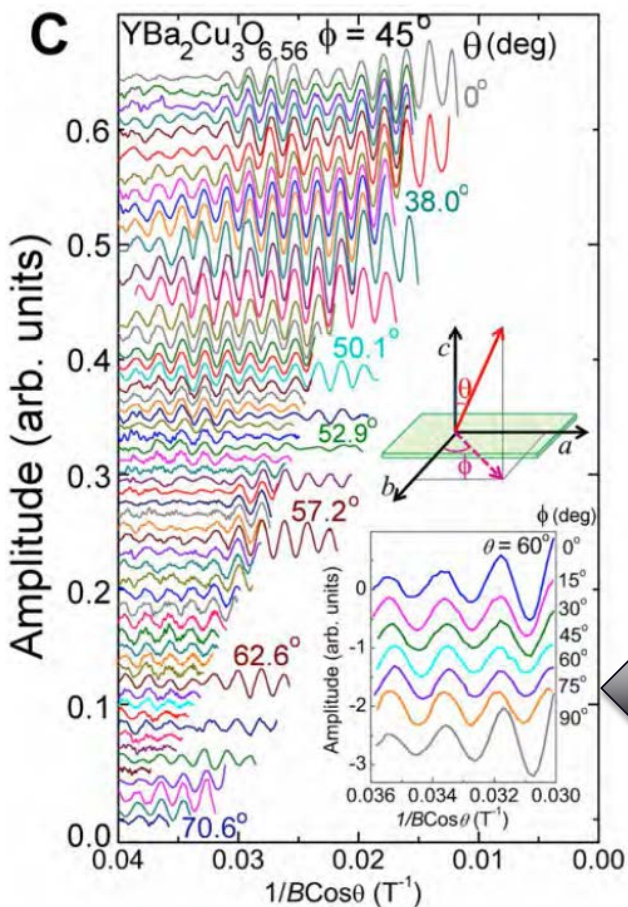
- Generally stress is nearly on the same level
- With Zylon and new CuNb conductor, coils 3 and 4 of the proposed outsert have lower stress level, possibly deliver higher field

Temperatures in the winding layers of proposed outsert magnet for a full-field pulse are all below 200 K

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6. Discussion on proposed plan to go beyond 100T
7. Some examples of cutting edge high-field science

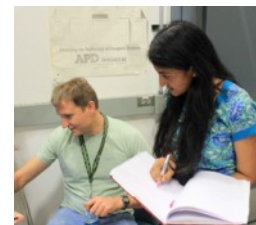
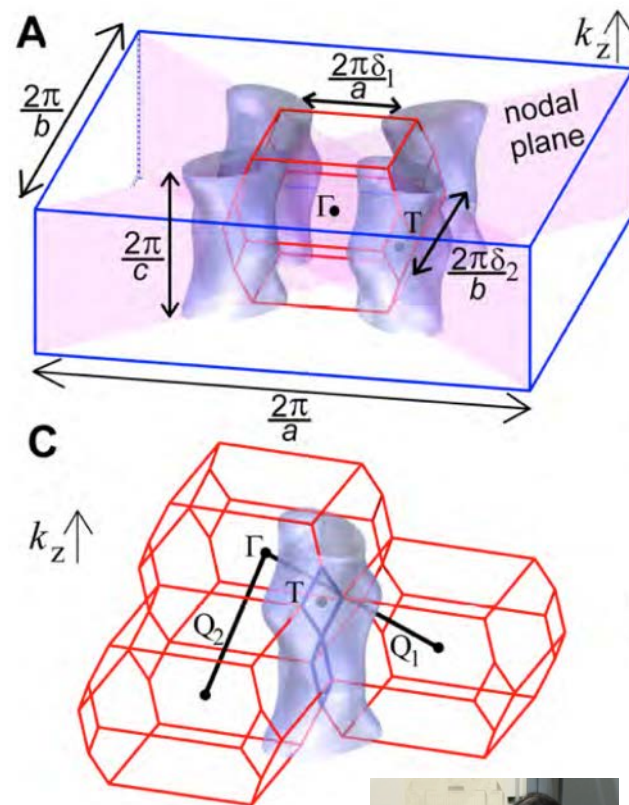
- Exhaustive work requires the best and most reliable technologies*



Quantum Oscillations are used to determine the cross section of the Fermi surface

Angular dependence is required to map out 3 dimensional momentum space

One 100T pulse
Sixteen 93T pulses
Fifty-six 65T pulses



Electronic excitations in atomically thin semiconductors

- Monolayer transition-metal dichalcogenides belong to a new class of atomically-thin semiconductors that show great promise for advanced optoelectronic applications
- Magneto-transmission spectroscopy in pulsed magnetic fields to 65 teslas revealed—for the first time—how the binding energy and size of the excitons depend on the dielectric constant of the surrounding material. This work shows that optical properties of 2D semiconductors can be tuned by design.

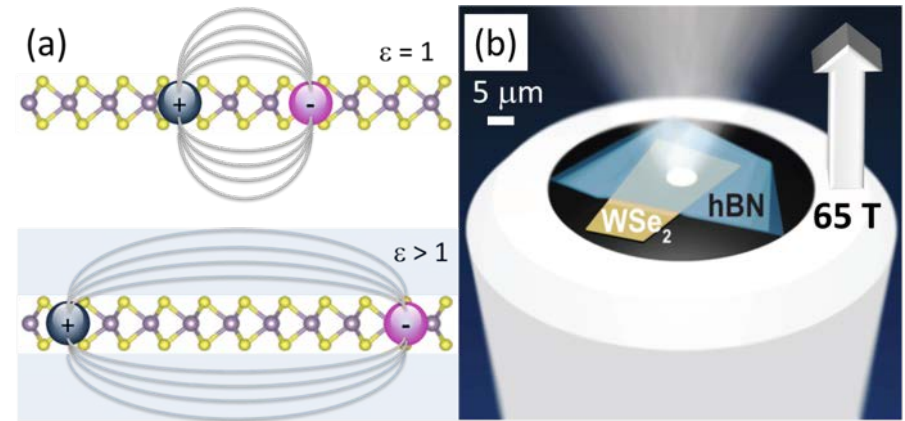


Figure 1: (a) 2D excitons in monolayer WSe_2 : As dielectric screening from the surroundings increases, their size grows and binding energy drops. (b) The experiment: monolayer WSe_2 is affixed to an optical fiber and encapsulated.

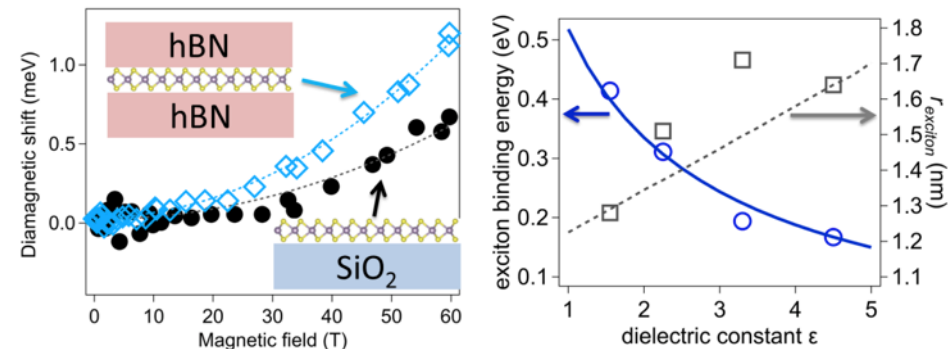


Figure 2: (a) Quadratic diamagnetic shift to 60T gives the exciton radius (r_{exciton}). (b) Calculated and measured exciton binding energy and r_{exciton} versus average dielectric constant ϵ of the surrounding environment.

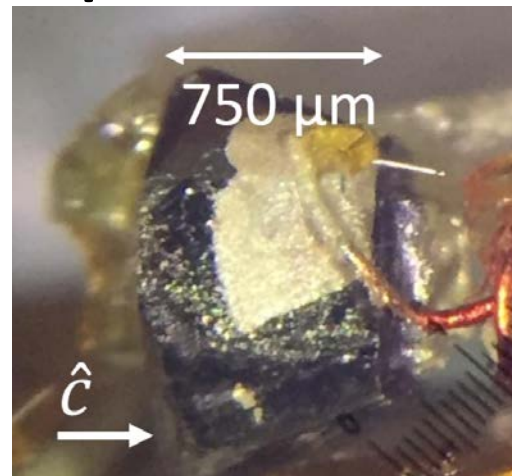
A.V. Stier, N.P. Wilson, J. Clark, X. Xu & S.A. Crooker, "Probing the influence of dielectric environment on excitons in Monolayer WSe_2 : Insight from high magnetic fields." *Nano Lett.* **16** (11), 7054-7060 (2016)



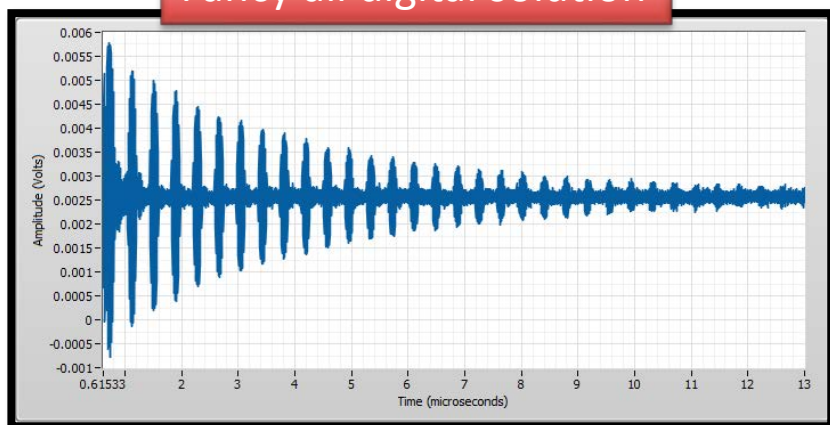


Thermodynamic signature of the field induced phase

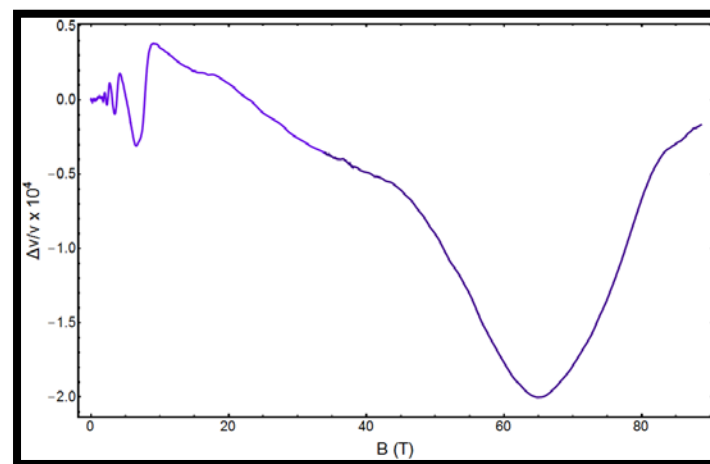
- pulsed echo ultrasound yields change in sound velocity and attenuation @ 300 MHz
- Y-cut LiNbO3 transducer
- $V \sim 5\text{ km/s} \rightarrow$ sub mm samples
- 100kHz pulse rep rate.
- Phase measurement of multiple echos gives 1pt in 10^6
- TaAs single cristal



Fancy all digital solution



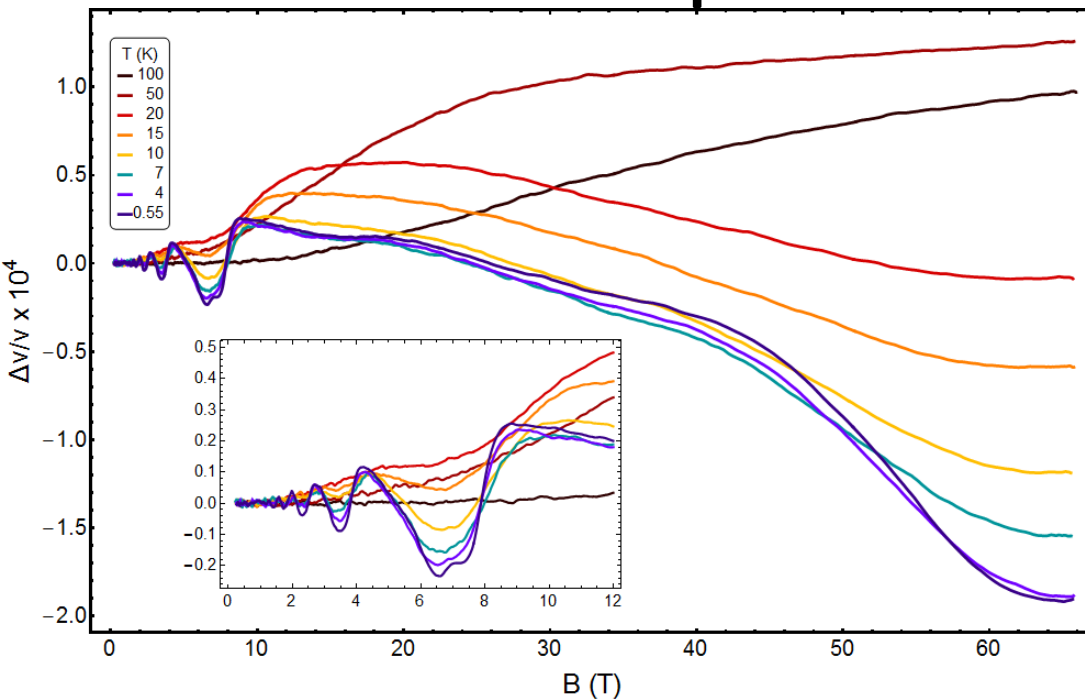
User: Brad Ramshaw \rightarrow Cornell



Change in the speed for $\sim k/B/c$, where $\sim k$ is the propagation wavevector of the longitudinal sound



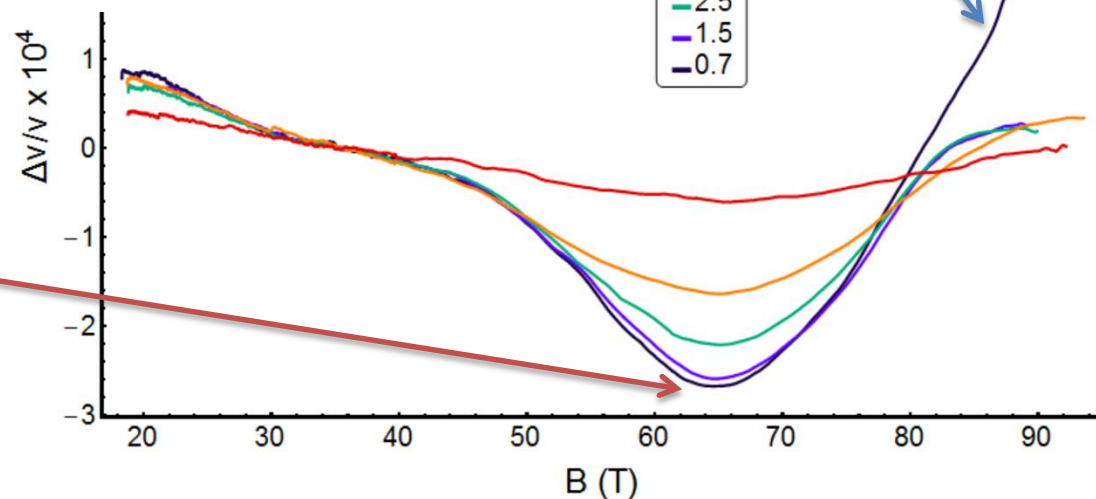
Sound speed in the quantum limit



Further discontinuity in the sound speed above 80T at the lowest temperatures

Well resolved quantum oscillations at low fields

Softening trend reverses above 65T

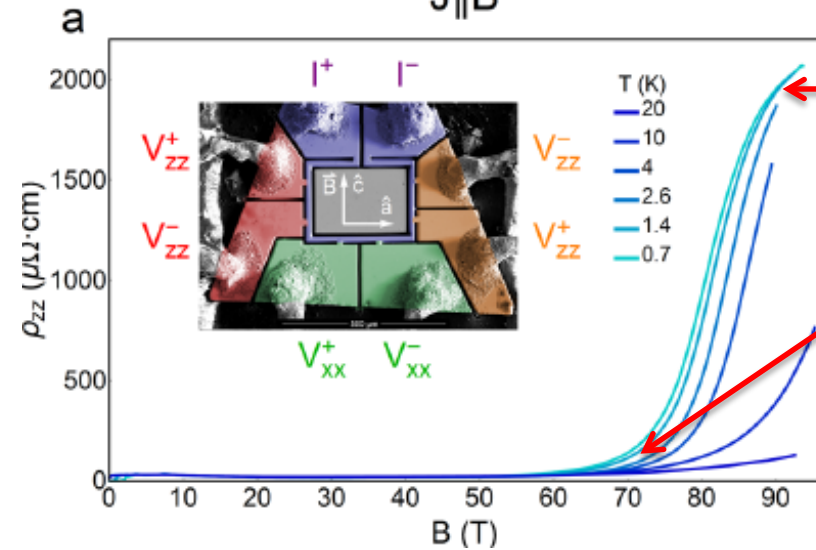




Similar behavior for transport and RUS measurement

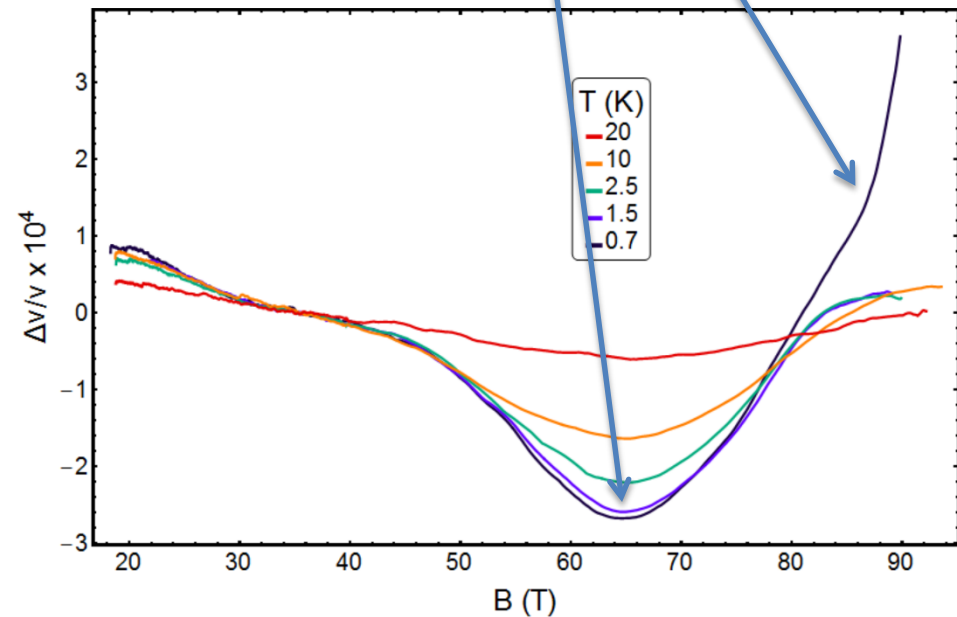
Transport measurement

$J \parallel B$



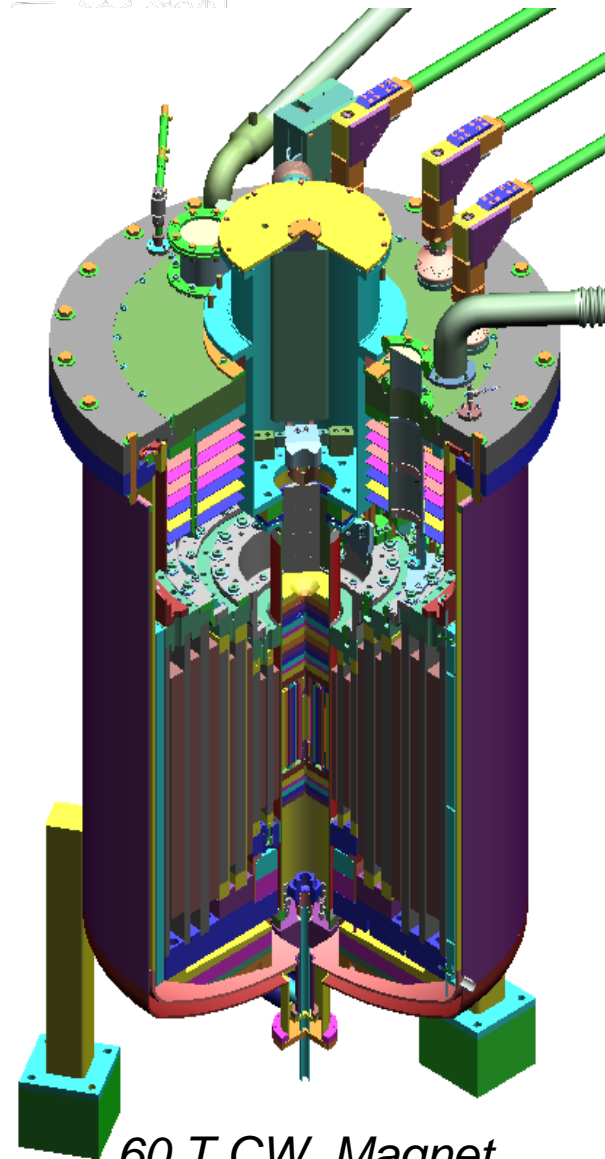
Further discontinuity in the sound speed above 80T at the lowest temperatures
Double phase transition?

Quite sharp increase in ultrasonic attenuation

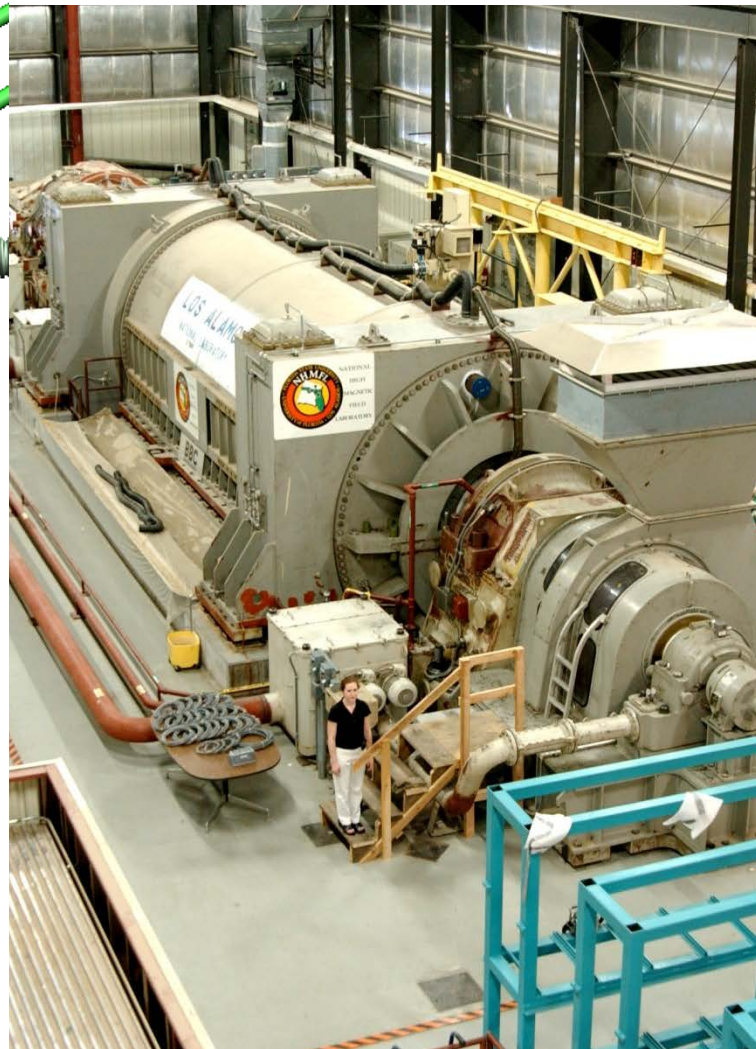


Brad Ramshaw:
arXiv:1704.06944v1 [cond-
mat.str-el] 23 Apr 2017

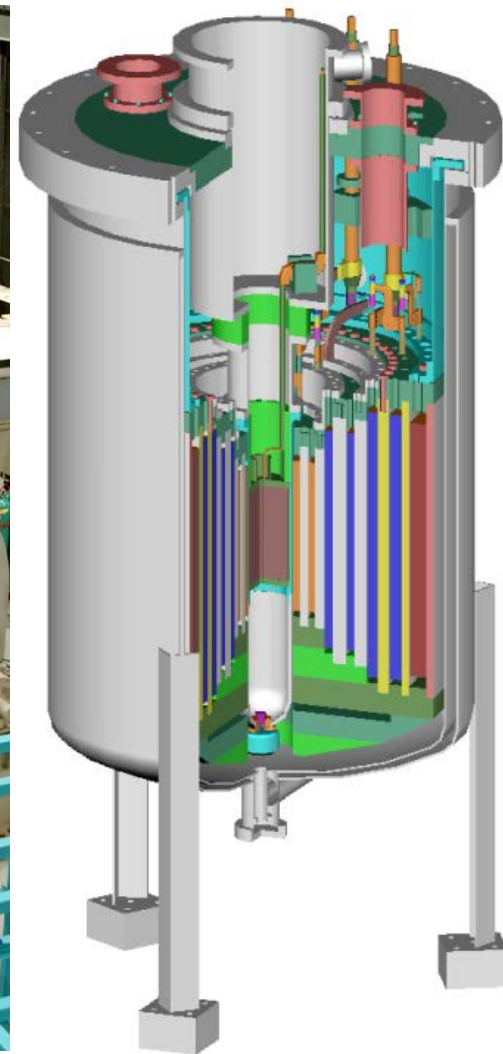
Thank You & Question



60 T CW Magnet



1.4 GW generator



100 T Magnet